

IS THE LOCAL BUBBLE DEAD?

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Abstract We give a summary of the current state of Local Bubble research, resulting from the discussions of a dedicated panel meeting. After more than 25 years of intense observational and theoretical work, we are still far from a coherent picture, although a probable one emerges at the horizon. A multi-supernova origin seems to be the best guess, with non-equilibrium cooling and soft X-ray emission accompanying its expansion. In addition our vantage point may force us to accept a substantial but quantitatively unknown contribution from heliospheric emission.

Keywords: Local Bubble, soft X-rays, superbubbles, Local Fluff, Interstellar Medium

1. Introduction

The Local Bubble Panel Session took place on the last day of the Galactic Tertulia meeting, and therefore lots of new exciting ideas that were spread during the meeting needed eagerly to be discussed. One of them was a suggestion put forward by Rosine Lallement, who together with her collaborator Barry Welsh, had investigated the possible contribution to the soft X-ray emission from charge exchange reactions of solar wind high ionization stages with heliospheric plasma, a process that had been successfully applied to X-ray emission of comets (Lisse et al. 1996; Cravens et al. 1997). We will discuss this in more detail below. On the whole the panel discussion on the Local Bubble was somewhat chaotic owing to active participation from the floor and a belated sudden discovery that our departure from the conference hall was soon required. This discussion was nominally led by Dieter Breitschwerdt (who had prepared a list of topics with the somewhat provocative title: “Is the Local Bubble Dead?”) and Don Cox (who played *advocatus diaboli* whenever necessary), and a number of interesting points were raised. Now with the leisure of writing them up, perhaps we can make the significance more transparent.

One way of organizing the material is via the questions and puzzles that remain, though perhaps for a broader audience, a survey of the ideas currently afloat would be a better way to begin. Many of the issues were discussed at length by Cox and Reynolds (1987). The continuing development of Don's perspective is pretty well summarized in three subsequent papers, one on the nature of the hot gas within the Local Bubble (Smith and Cox, 2001), one on a possible origin of the warm Local Fluff within the hot bubble (Cox and Helenius, 2003), and one which discusses the possibility that the whole effort is a house of cards (Cox, 2003). Dieter has written a few review papers (Breitschwerdt 1996, 2001), emphasizing the problems of explaining EUV and soft X-ray spectra by the conventional Local Hot Bubble model, which is based on collisional ionizational equilibrium (CIE), and also a paper on the possible origin of the bubble (Berghöfer & Breitschwerdt 2002). Many others have contributed to the effort to understand the local interstellar medium in general and the Local Bubble in particular. Dieter organized a whole conference on the subject in Garching in 1997. Participants at the Granada conference who have wrestled with the subject include at least (we apologize for any incompleteness): Avillez, Beckman, Breitschwerdt, Cox, Edelstein, Gry, Hartquist, Helenius, Hurwitz, Korpela, Kuntz, Lallement, Maíz-Apellániz, McCammon, Reynolds, Sanders, Shelton, Welsh. Most of these are people who actually measure things, and have some truth to tell. One person not at the Granada meeting, Priscilla Frisch, has written extensively on the observational material available concerning the local region. This should be a sufficient list from which to start a literature search should one wish.

2. The Situation in General Terms

Soft X-rays reach the Earth in a pattern that shows a distinct anti-correlation, in particular of 1/4 keV photons with the distribution of local interstellar material (see Fig. 1 for NaI absorption line studies and Rosine Lallement's updated figure at this conference with a much larger number of stars). The emission is diffuse, meaning that it does not arise from a collection of unresolved point sources. The pattern is roughly what might be expected from extragalactic emission, absorbed by galactic interstellar material, except: A) it does not go to zero in the galactic midplane, and B) the very lowest energy X-rays ought to be much more absorbed, but instead show a very similar distribution. Therefore there must be a local source of diffuse emission. Attempts to localize the source of the emission have used shadowing by intervening material of putatively known distance. McCammon's thesis work showed that it arose closer than the Magellanic Clouds. Shadowing experiments done with ROSAT, EUVE, and as reported by Dieter at this meeting with XMM-NEWTON, have had more restrictive results. At high galactic latitude, there are clouds of ma-

terial several hundred parsecs from the Sun that shadow *part* of the X-ray emission. So, some arises within the first few hundred parsecs (and much closer at lower latitudes where absorbing and/or abutting walls of interstellar material are much closer) and at high latitude, part arises from further away.

This more distant emission is very patchy over the sky, and is the origin of the idea that the Milky Way has a patchy distribution of hot gas within its “halo.” The word halo is in quotes because Don thinks of the disk of the Galaxy as reaching up a kiloparsec or more and that this emission is likely found within it, not in some vast region beyond. This particular point is open to dispute, but will likely not be settled until we have a better understanding of why the very lowest energy emission does not have a substantially different distribution on the sky. It was early on realized that this emission resembled that from a hot interstellar plasma with a temperature of roughly 10^6 K. Plasma emission models based on CIE suggested that the surface brightness could be achieved in a volume extending 100

pc with a thermal pressure comparable to that expected in a large hot cavity in equilibrium with its surroundings, $p/k \sim 10,000 - 20,000 \text{ cm}^{-3} \text{ K}$. The so-called “displacement” or Local Hot Bubble (LHB)” model, put forward almost simultaneously by Wisconsin (Sanders et al. 1977) and a Japanese group (Tanaka and Bleeker 1977) could explain satisfactorily at that time the local soft X-ray emission by claiming that *all* of the emission in the 1/4 keV band was due to a hot plasma of $\sim 10^6$ K and $n_e \sim 5 \times 10^{-3} \text{ cm}^{-3}$, displacing neutral surrounding gas¹. A roughly contemporaneous result was that absorption line studies were finding that the region around the Sun in fact has very little interstellar material for the nearest hundred parsecs or so, depending on direction. (As mentioned above, the papers by Lallement and by Welsh at this meeting

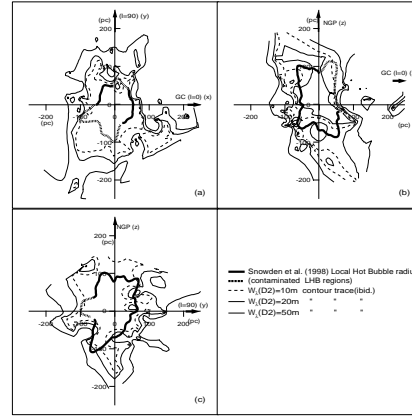


Figure 1. The local cavity as inferred from NaI absorption line studies by Sfeir et al. (1999) at different viewing angles. The different contours mark different NaI equivalent widths, with 20 mÅ corresponding to $\log(\text{NaI}) = 11.0 \text{ cm}^{-2}$ or $N_H \approx 2 \times 10^{19} \text{ cm}^{-2}$. The thick solid line represents the contour of the Local Bubble according to ROSAT PSPC observations by Snowden et al. (1998).

¹When the first ROSAT shadow of the Draco Nebula was discovered (Snowden et al. 1991, Burrows & Mendenhall 1991) it became evident that roughly 50% of the 1/4 keV emission was arising from beyond the cloud, i.e. at a minimum distance of 300 pc and thus far beyond the Local Bubble.

show the current state of mapping that cavity.) The cavity has a very irregular geometry, but extends to several tens of parsecs in the galactic midplane and opens at high (and low) galactic latitudes where it extends further than has been mapped so far, several hundred parsecs (see Fig. 1). And, it is precisely in those seemingly open directions that EUVE was able to detect extragalactic objects.

3. “The Devil is in the Details”

Because of its extreme faintness and the technological limitations on spectral resolution, the soft X-ray background has been slow to reveal its full spectral character. The measurements are often compared with those expected from hot plasmas with solar abundances, by calculating CIE emission spectra (vs. T and absorbing column) and folding the latter through the instrumental response. Best fits are made in the usual way, with one or two emitting temperature components. The spectra that produced the best fits to the 1/4 keV X-rays also predicted softer emission, particularly a very bright iron complex around 72 eV. They also predicted little oxygen K-shell emission. Several attempts to verify the brightness of the soft iron lines failed to detect them, until finally they seem to have been seen by XQC at roughly 1/7th of the initially anticipated brightness—see paper by McCammon in this volume. To continue spectral fitting in the above way, one must assume that iron, at least, and possibly other elements remain somewhat depleted in their abundances in the hot gas. (Smith and Cox, 2001, showed that this is feasible so long as the gas has not been heated too many times.) The spectral results of DXS, on the other hand cannot be fit very well by this process (Sanders et al. 1998), seeming to require considerable improvement in the plasma modeling codes or, perhaps an alternative source type for a significant fraction of the emission—more below on this point.

At the higher energies of the 3/4 keV band, Snowden et al. (1993) analyzed ROSAT PSPC data towards MBM12, commonly believed to be a medium latitude cloud within the Local Bubble at a distance d of $58 \pm 5 < d < 90 \pm 12$ pc (Hearty et al. 2000; but see recent photometric analysis of M dwarfs by Luhman (2001) who place it out to 275 pc just to add more devilish details to the puzzle). They found that all of the 3/4 keV band emission seemed to come from beyond the cloud, and set a fairly strong upper limit to the foreground emission, that attributed to the hot Local Bubble, and to its temperature (found as described above). On the other hand, together with Michael Freyberg, Dieter reanalyzed these data, as well as data from the Aquila molecular cloud, which is one of the darkest nearby regions of the diffuse X-ray sky, and located in almost the opposite direction. On the basis of these data, including higher energies than analyzed by Snowden et al., they derived a new value for a local component which is $kT = 0.18$ keV ($\sim 2.1 \times 10^6$ K), much higher than previous values. There was clearly cause for some disagreement.

The latest XMM-Newton observations done by the group in Garching (MPE) show the presence of emission near 0.56 keV and 0.65 keV (indicating OVII and OVIII, respectively) for all targets, situated in different directions and at different distances and latitudes in the sky, e.g. MBM12, G133-69 (in the southern hemisphere), North Galactic Pole Rift (NGP) and the Ophiuchus molecular cloud (see Figs. 2 and 3). This is fully consistent with the X-ray quantum calorimeter (XQC) results (see Fig. 4) by McCammon et al. (2002). Although the spectral resolution of XQC is much higher than of the EPIC pn camera, the short duration of the sounding rocket flight required observing a region that covered both Local Bubble and Galactic halo. The shadowing observed, for example in Fig. 2 allowed separation of the local and distant emission, and a two component spectral fit to the foreground yields temperatures of 0.08 and 0.14 keV, respectively.

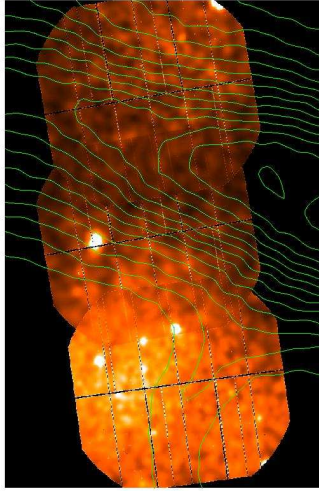


Figure 2. Mosaic of three individual pointings of the Ophiuchus molecular cloud, showing the first XMM-Newton X-ray shadow (in the range 0.5 – 0.9 keV). There is a clear anticorrelation between soft X-ray emission and the overlaid IRAS 100 μ m contours. The color coding represents the X-ray intensity with white being the maximum.

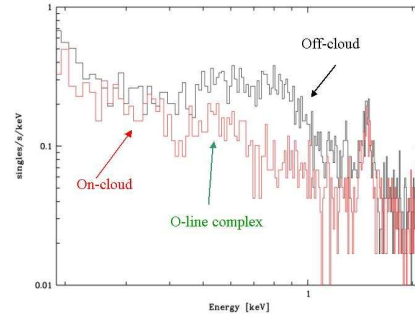


Figure 3. Spectra (in counts/s/keV) towards the Ophiuchus cloud as derived from two 20 ksec XMM-Newton EPIC pn observations. Emission line complexes are clearly distinguishable at 0.5 – 0.7, and \sim 0.9 keV, and to a minor extent at \sim 0.3 keV. The on-cloud pointing (lower curve) contains mainly emission from the Local Bubble, while the off-cloud (upper curve) observation has also significant contributions from the Loop I superbubble showing up as 0.8 – 0.9 keV emission (Fe-L complex), and arising from higher temperatures there.

The bottom line at present appears to be that the spectrum has less emission from the iron complex around 72 eV, other characteristics suggestive of maybe some depletion of refractory elements, and somewhat more oxygen K-

shell emission than expected from a contemporary single temperature solar abundance plasma model assuming CIE that fits best the softer emission.

Robin Shelton reminded us of more problems lurking in the back by mentioning recent FUSE ($905 < \lambda < 1195 \text{\AA}$) data: inside the Local Bubble the 2σ upper limit on the surface brightness of OVI (resonance line emission at $\lambda\lambda 1032, 1038 \text{\AA}$) is extremely low, at most 530 and $500 \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, respectively (Shelton 2003), in disagreement with all current models. She also thinks that such a low limit would rule out the possibility, put forward by John Raymond at this conference, to explain the complicated spectra by a superposition of different X-ray emitting and absorbing chunks of gas within the line of sight.

4. Whence the Local Bubble

Determining the spectrum of the soft X-ray background is just a first step in trying to understand the origin and the further evolution of the bubble. Models are needed too. The energy content of the hot gas bubble (The Local Bubble, as distinct from The Local Cavity) described before is roughly that of one supernova, and various models for the reheating of a portion of the Local Cavity by a relatively recent supernova have been made. The earliest models, as the one by Cox & Anderson (1982), assumed that the remnant was young, about 10^5 years old, so that its expansion velocity would give a post shock temperature of 10^6 K. Those models were found to have various problems and gradually gave way to attempts to model the bubble as more like a ‘‘Slavin Bubble’’, the old hot remnant of a supernova explosion (cf. also Innes & Hartquist, 1984) that has largely equilibrated in pressure with its surroundings. The Smith and Cox (2001) paper referred to above is a recent version. The reheating supernova was inferred to have occurred roughly 3 Myr ago, somewhere in the vicinity of the Sun. Independent evidence for the occurrence of such a supernova (cf. Knie et al.² 1999) was cited with glee. Until recently, the spectral confirmation that the X-ray emission actually arises from hot gas has been very poor. Some expected spectral lines have now been seen, but not all characteristics of the observed emission are consistent with existing models of hot gas. Encouraged by some problems in the interpretation of data (e.g. the region of ‘‘bizarre emptiness’’ as Don put it towards β CMa, or the thermal pressure imbalance between the LHB and the Local Fluff, a partially ionized cloudlet surrounding the solar system, as well as a probable inconsistency between EUV and soft X-ray data) Breitschwerdt and Schmutzler (1994) seized upon this weakness to propose an

²These authors have analyzed the ferromanganese crust of deep ocean layers, and found an enhancement of ^{60}Fe consistent with an explosion at about 5 Myr ago.

alternative model that bedevils³ us to this day. In this model, relatively high density material heated by one or more supernovae expanded very rapidly into a surrounding low density region, cooling adiabatically to low temperature as it did so. The expansion was so rapid that high stages of ionization characteristic of the initially high temperature were “frozen in” as occurs in the Solar Wind. They proposed that the subsequent recombination of those high ions to be the source of the soft X-ray background. A telling feature of such a recombination spectrum was expected to be the recombination continua, which at such low temperatures would resemble asymmetric emission lines at the recombination edges.

One can get into quibbles about the likelihoods of various scenarios, but it is safer to examine the predictions and the data and to try to understand what we are seeing. It is likely that the Breitschwerdt and Schmutzler scenario has occurred somewhere. To decide whether it is related to our soft X-ray background, however, we need good spectra. The current status of obtaining such spectra was summarized at this meeting by McCammon or Sanders, or both. We have DXS and XQC, and we desperately need a SMEX or MIDEX. Nobody is just going to hand us the data, even though detector development has reached the point that the crucial questions can be addressed.

Meanwhile, the whole field has been complicated by the strong possibility that a Breitschwerdt-like mechanism is operating to create much of the soft X-ray background within the Solar System! Those high stages of ionization in the Solar Wind mentioned earlier can undergo charge exchange on neutral atoms, and the subsequent cas-

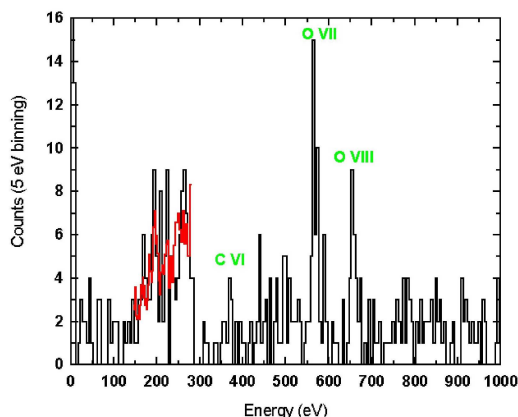


Figure 4. High resolution spectrum of the diffuse soft X-ray background (black histogram, arbitrary units) in the 70 - 1000 eV energy range, taken with the XQC spectrometer during a 100 s sounding rocket flight (McCammon et al. 2002). The instrument FOV was about 1 sr and centred at $l = 90^\circ$, $b = 60^\circ$. Prominent emission lines are marked. The DXS spectrum taken from a region near the Galactic plane (Sanders et al. 2001) is superposed (grey or red lines, respectively, in the energy range 150 - 284 eV) for comparison.

³These are Don’s words; Dieter agrees that the model is somewhat bold, owing to his youth at that time, but still believes that the Local Bubble spectrum has to be some kind of “non-equilibrium”, even if it were as extreme as produced by Solar Wind charge exchange reactions in the heliosphere.

cade creates copious X-rays. This mechanism is believed to be responsible for the extremely bright X-ray emission from comets in the inner Solar System. Comets do not supply the only neutral targets for charge exchange in the Solar System, however. There are now strong indications that a temporally fluctuating component that was spectrally indistinguishable by ROSAT from the soft X-ray background (the “Long Term Enhancements”) derives from Solar Wind charge exchange on the exosphere of the Earth! But the Earth is not the only other target. Using estimates of the charge exchange cross sections, it is easy to calculate the approximate level of X-ray emission from charge exchange of Solar Wind ions encountering interplanetary neutrals (e.g. Cox, 1998). The answer is frighteningly large! The current situation is presented in Lallement’s paper in this volume, where she has integrated the solar wind flux against the interstellar distributions of hydrogen and helium, *in the directions and for the times at which ROSAT was making the survey*. This provides a spatial template against which to measure the potential contamination. Her paper goes on to assume various normalizations, based on the poorly known cross sections and ionic populations, and then subtracts off the heliospheric contribution to see what is left of the Local Bubble. She points out that what is left correlates better with the structure of the spatial cavity (discussed above) than did the total SXRb.

How much is she subtracting? Within the uncertainties, *all* of the SXRb in the galactic midplane could be heliospheric! This still leaves quite a lot at high (positive and negative) latitudes that can’t be heliospheric, along with some extended regions at lower latitudes that correlate with the surrounding structure. She seems to prefer to preserve the Local Bubble, perhaps to preserve those lobes as part of it, and therefore to propose subtracting only, say 50 to 80% of the emission in the lowest emission directions. This is as good and responsible a guess as anyone can make at this time. We need both better heliospheric emission models and measured spectra before much progress can be made.

Does this require a disastrous change in our view(s) of the hot Local Bubble? She argues not. Suppose, for example, that in some low latitude directions the Local Bubble emission is only 25% of what we previously thought. As emissivity goes as density squared, it would imply that the density and pressure were halved. At high latitudes, where the subtracted fraction is much less, a four times greater path length would be required to get the observed brightness, and the extension of the Local Bubble to beyond the shadowing clouds would be a fairly natural consequence. The total energy in hot gas may then exceed that which one supernova could supply, but living in a very large bubble makes multiple supernovae much more likely.

Dieter has ventured to construct such a model (Berghöfer & Breitschwerdt 2002), and interestingly, at around the same time a similar idea was put forward by Maíz-Apellániz (2001), who also presented his views during the panel

session. The basics are very simple. As has been mentioned above, the X-ray emissivity of the Local Bubble can easily be accounted for by one or two recent supernovae, whereas it took considerably more explosions to blast the Local Cavity free of gas; about 10 - 20 supernovae can do this. But there are no early type stars within the Local Bubble. On the other hand there are plenty in the nearby Sco-Cen association. Stellar kinematics data show that one or several moving groups of young stars have passed through the Local Bubble on their way to Sco-Cen. Fitting an IMF appropriate for galactic OB associations to such a group, Berghöfer & Breitschwerdt (2002) were able to calculate the sites of explosions and the intervals between them. Recent high resolution simulations on a large grid (including the galactic fountain, for details see the contribution of M. Avillez, this volume) and occurring in an inhomogeneous background, disturbed by previous generations of supernovae have shown (Avillez & Breitschwerdt 2003) that both the morphology and the timescales of the Local Bubble and the Loop I superbubbles are consistent with observations.

The numerical simulation presented of this activity was quite striking, and at several times appeared to show filaments or sheets of material intruding into the hot gas. Sometimes these appeared to be of the sort advocated by Frisch, material ejected from near the wall by recent explosion activity there. At other times, they may have arisen from shear flows in the highly convective medium. What could not be discerned in the time available was whether they occasionally derived from a mechanism proposed recently by Cox and Helenius (2003), filaments of material pulled from the boundary through the hot gas by magnetic tension. At least one of the panelists thought this had to be the case. Distorted magnetic fields of the magnitude observed in the interstellar medium are very quick to straighten themselves out when they have very little material on them, with only hydrodynamic drag through the surroundings to slow them down. This view was discussed briefly at one of the sessions and argued against on the basis of the resulting ionization of helium and argon, compared to the observations. This led to discussion of the sorry state of our knowledge of low temperature dielectronic recombination in particular, and recombination of things like argon in general. Enough smoke, and the issue was left hanging.

This question of the ionization in the Local Fluff fascinates a number of people, as does the issue of the apparent thermal pressure imbalance between the Local Fluff and the surrounding hot gas. Attempts to cure the latter with a strong magnetic field in the Fluff run into constraints from Voyager 1 not yet having encountered the Solar Wind termination shock. Having run out of space, we refer the reader to discussions of these matters in Cox and Helenius (2003). (Dieter wants to point out that neither of these problems exists in his bedeviling model, however.)

5. Conclusions

The Local Bubble is still an active and highly relevant research topic and will keep surprises for the people who venture to learn more about it. From time to time there will be bold attempts to get rid of it, as it has happened in the past, when it was thought to be an interarm region, or now, that some believe that much of its X-ray emission could be of heliospheric origin. Yet the cavity is still with us. We have both been working long enough in the field to think that the emblem for the City of Paris will also hold for the future of the Local Bubble: *fluctuat nec mergitur!*

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